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ASSESSING FLUSHING-FLOW REQUIREMENTS FOR BROWN TROUT SPAWNING GRAVELS IN STEEP STREAMS[1]

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ABSTRACT: Flushing flows are releases from dams designed to remove fine sediment from downstream spawning habitat. We evaluated flushing flows on reaches proposed for hydroelectric diversions on seven streams in the eastern Sierra Nevada, California, with wild populations of brown trout (*Salmo trutta*). The stream reaches are steep (average map slopes range from 7 to 17 percent), are dominated by boulder cascades, and afford few opportunities for gravel deposition. Methods for estimating flushing flows from flow records, developed from studies in other localities, produced widely differing results when applied to the study streams, probably reflecting differences in the hydrologic and geomorphic characteristics of the streams on which the methods were developed. Tracer gravel experiments demonstrated that all sampled gravels were washed out by the flows of 1986, a wet year. Size analyses of gravel samples and hydraulic data from field surveys were used in tractive-force calculations in an attempt to specify the flow required to flush the gravels. However, these calculations produced some unrealistic results because the flows were nonuniform in the study reaches. This suggests that the tractive-force approach may not be generally applicable to small, steep streams where nonuniform flow conditions prevail.

(KEY TERMS: flushing flows; instream flow needs; Brown trout (*Salmo trutta*); spawning gravel; tracer gravel movement.)

INTRODUCTION

All wild salmonids begin their lives as eggs buried in streambeds. As such, their survival and production are limited, in part, by the areal extent and permeability of potential spawning gravels, as well as the adequacy of streamflow over them (Allen, 1969).

Hydroelectric impoundments and diversions can affect the quality of salmonid spawning gravels by altering the quantity and timing of stream flows, as well as the downstream sediment load (Williams and Wolman, 1984). Dams can alter flow regimes by changing the characteristics of a stream's flow-duration curve or by producing a net reduction of annual discharge within the by-passed reach. If high flows that occurred under natural conditions are not released from the dam, fine sediment can accumulate in streambed gravels, reduce the permeability, and lessen the suitability of the gravels for spawning and for survival of incubating embryos. Dams also trap sediment from upstream and thereby affect streambed gravels by changing sediment delivery to downstream reaches. Large dams often trap sediment for the lifetime of the impoundment, but small diversion structures are frequently equipped with sluice gates that can be opened periodically to allow accumulated sediments to pass downstream.

To remove accumulated sediments from important fisheries habitats, periodic high-flow releases designed to flush fine sediment from gravels are often recommended. These "flushing flows" may also be designed for maintenance of the channel cross section and riparian vegetation (Reiser, *et al.*, 1985).

In the Owens River basin, California, license applications are pending for small (< 5 MW) hydroelectric projects that would divert water into penstocks from seven streams in the eastern Sierra Nevada, California. Because of the need to assess possible cumulative impacts of many small projects clustered in a single river basin, the Federal Energy Regulation Commission (FERC) has recently applied the Cluster Impact Assessment Procedure (CIAP) in the Owens River basin (FERC, 1985, 1986). The proposed hydroelectric projects would divert water from sections of the streams inhabited by self-sustaining trout populations. The potential impact of these proposed projects on spawning gravels needed for trout reproduction was an issue of concern. The studies described herein were conducted in support of the Owens River basin CIAP and were designed to assess flushing flow requirements for the reaches proposed for diversion.

STUDY AREA

The study reaches are located on tributaries to the Owens River draining the eastern slope of the Sierra Nevada, in Mono and Inyo counties, California (Figure 1). The relief is remarkably steep along the mountain front on the western side of the basin, with peaks over 4,000 m high rising above the floor of the Owens Valley (elevation below 2,000 m), less than 30 km away. Precipitation occurs primarily as snow deposited at higher elevations. East of the Sierra Crest,

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the Owens Valley lies in a rain shadow; the town of Bishop receives 145 mm of precipitation annually (California Department of Water Resources, 1980). Accordingly, most of the runoff in the study streams comes from snowmelt high in the watershed, and annual hydrographs are characterized by high summer snowmelt flows and low winter base flows. Drainage areas for the study streams range from 21 km^2 (Tinemaha Creek) to 98 km^2 (Pine Creek); mean annual flows range from 0.12 m^3/s (Red Mountain Creek) to 1.3 m^3/s (Pine Creek). Recording stream gages are maintained on all affected streams by the Los Angeles Department of Water and Power (LADWP) (Figure 1).

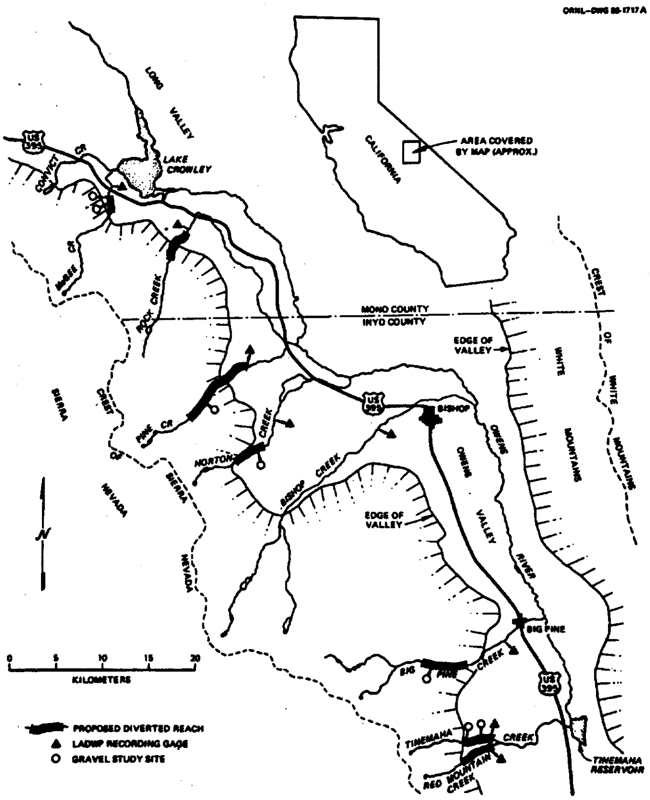

Figure 1. Location Map Showing Streams Proposed for Hydroelectric Development. Reaches to be by-passed by the proposed projects are stippled, Los Angeles Department of Water and Power recording gages are designated by solid triangles, and gravel study sites are designated by open circles. (Based on Mariposa Sheet, U.S. Geological Survey 1:250,000 series.)

The proposed new hydroelectric projects considered in the FERC CIAP would divert water from portions of seven streams through penstocks to powerhouses located downstream of the diversions (Figure 1); they would operate in a run-of-the-river mode, having generating capacities from 950 kW to 4200 kW. The shortest proposed diversion (or by-passed reach) is under 2 km (McGee Creek); the longest is about 9 km (Pine Creek). All the diverted reaches are steep, with average slopes ranging from 7 percent (Pine Creek) to 17 percent (Horton Creek), as measured from topographic maps. Potential spawning gravels are not abundant in the study reaches. They tend to occur in reaches of lower-than-average gradient, either as small patches in sites of flow divergence or as larger deposits upstream of major controls (Kondolf, *et al.*, in press).

Although the Owens River basin was originally devoid of trout, historical stocking efforts have established populations in the Owens River and many of its tributary streams on the eastern slope of the Sierra Nevada Mountains. Brown trout (*Salmo trutta*) are by far the most successful of the introduced trout species; in a recent survey of the trout resources of the Owens River drainage (Deinstadt, *et al.*, 1985), brown trout were collected at 69 of 80 stream sections and accounted for 84 percent of the trout biomass sampled. Owens River tributary streams are extremely productive; the median standing crop for all sites sampled was 108.5 kg/ha, and standing crops greater than 200 kg/ha were not unusual (Deinstadt, *et al.*, 1985).

METHODS

Existing methods for estimating flushing flows can be placed into two general categories: 1) those that assume that "nature knows best" and that the flushing flow should mimic the natural flow regime in some specified way, and 2) those that use direct observation and/or calculation from engineering formulae of the flows needed to entrain the gravels at sample sites.

Estimation of Flushing Flows from Flow Records

Reiser, *et al.* (1985), reviewed 15 methods for assessing flushing flows. Of these, seven rely on a statistic from historical flow records. The statistic may be some multiple of the average annual flow, a specified value from the flow duration curve, or flow with a specified recurrence interval from a flow frequency analysis. An example of the first type is the widely used Montana method, which recommends 200 percent of the average annual flow (Tennant, 1976). Average flow data were available for all study streams, so this was one of the methods we applied.

Reiser, *et al.* (1985), reviewed two methods that rely on a statistic from the natural, preproject flow-duration curves. The Hoppe Method recommends a 2-d (2 day) release of the flow that was equalled or exceeded 17 percent of the time under natural conditions (Q_{17}) (Hoppe, 1975; Hoppe and Finnell, 1970). The second method was developed by Reiser, *et al.* (1985), from research results by Beschta and Jackson (1979). This method recommends releases of the flow equalled or exceeded 5 percent of the time under natural conditions (Q_{05}). We applied these methods to flow duration curves presented in license applications. However, at least some of these flood duration curves were developed from mean monthly flows instead of mean daily flows, so some values, especially for Q_{05}, may be low.

The third category of methods for recommending flushing flows from flow records involves selecting a flow having a specified recurrence interval on the flood frequency curve. Using the results of geomorphological studies indicating that the channel is influenced primarily by flows with a recurrence interval of 1.5-2.0 years (e.g., Wolman and Leopold, 1957; Leopold, *et al.*, 1964; Andrews, 1980), these methods prescribe the 1.5 to 2.0-year flood to flush stream bed gravels and maintain channel form. Reiser, *et al.* (1985), provides a review of three such methods. Flood frequency curves were not available for all our study streams, so we did not apply these methods.

Estimation of Flushing Flows from Bed Mobility Observations

A very different approach to estimate the flushing flow at a site is to observe bed mobility over a range of flows. Assuming that interstitial fine sediment will be flushed from the gravel when the gravel is in motion, the flow at the threshold of motion becomes the prescribed flushing flow. Geomorphologists have monitored bed mobility directly by observing the threshold of movement for tracer gravels and by documenting scour using scour chains (Leopold, *et al.*, 1966), or indirectly by sampling bedload in transit (Andrews, 1983). These studies have shown that bed mobility varies from site to site within a stream (e.g., from riffles to pools), so tracer gravels or scour chains must be emplaced directly in the gravel deposits of interest.

Reiser, *et al.* (1985), reviewed several approaches to flushing-flow assessment by monitoring bed mobility, including the methods of Hey (1981) and O'Brien (1984). For this study, these approaches could not be used to pinpoint flows producing entrainment because we were not present at the field sites during high snowmelt flows. However, during gravel sampling and field surveys in August 1985 we emplaced a total of 445 tracer gravel particles at nine sites in the beds of four of the five streams surveyed to monitor bed mobility over the 1986 flow season, a wet year with 160 percent of normal runoff. The tracers emplaced at each site were natural gravels larger than 25.4 mm (1 inch) from the samples of potential spawning gravel we obtained from the site. After being air-dried, sieved, and weighed, the gravels larger than 25.4 mm were spray-painted and replaced in the bed at the same location from which the sample was obtained. In most cases, the sampler was left in the bed during the procedure so that the painted sample could be reinserted in the bed through the sampler. The size of the tracer gravels used (mostly under 64 mm) reflected the size of the potential spawning gravels from which they were drawn. To provide information on the movement of larger particles, 14 cobbles (ranging from 64 to 215 mm in diameter) were painted and emplaced in Pine Creek. The tracer gravel sites were reoccupied in October 1986 to observe whether the painted rocks had moved.

Flushing Flows Computed from Entrainment Functions

When bed mobility cannot be observed over a range of flows (as was the case in this study), engineering formulae can be employed to calculate the flow at which bed material should begin to move. The threshold of motion depends on the particle size of the gravel (the bigger the gravel, the more force required to move it) and the water-surface slope and water depth over the gravel (the deeper and steeper the flow, the greater the force exerted by the water). The approach most widely used to estimate the threshold of movement for bed material is to calculate shear stress (force per unit area) exerted by specific flows and compare those values with the critical shear stress, which is the shear stress required to entrain the bed material (Leopold, *et al.*, 1964; Vanoni, 1975). Reiser, *et al.* (1985), developed an application of this approach to estimate flushing flows. Our analysis uses the shear stress approach as well, although somewhat differently.

Critical shear stress can be computed from the Shield's function,

$$\tau_{ci} = \tau^*_{ci} (\gamma_s - \gamma_f) D_i \tag{1}$$

where τ_{ci} is critical shear stress in N/m^2 for a particle size designated by i, τ^*_{ci} is a dimensionless shear stress, γ_s is the specific weight of the solid (N/m^3), γ_f is the specific weight of the fluid (N/m^3), and D_i is the diameter of particle i (m). For the conditions prevailing in natural strams having bed material larger than 2 mm, a constant value of 0.060 for τ^*_{ci} is indicated by the Shields' diagram (Vanoni, 1975). The actual value varies as a function of the size distribution of heterogeneous bed material. The average of wide-ranging values from field observations is about 0.060 (Andrews, 1983), which is the value we have used here.

Equation (1) can be simplified by assuming a specific gravity of 2.7 for the solid and assuming the specific weight of the fluid to equal that of clear water at 4°C, or 9,806 N/m^3:

$$\begin{aligned} \tau_{ci} &= \tau^*_{ci} (2.7 - 1)\, \gamma_f D_i \\ &= (0.060)\,(1.7)\,(9806\ n/m^3)\, D_i \end{aligned}$$

$$\tau_{ci} = 1000.21\, D_i \tag{2}$$

Potential spawning gravels were sampled in five of the seven study streams. Methods and results of gravel sampling and size analyses are presented in Kondolf, *et al.*, in prep.). We used the median diameter (D_{50}) of our gravel samples for D_i. Because the operations of converting D_{50} from millimeters to meters and multiplying by the constant in Equation (2) cancel each other, the resulting values of τ_{ci} in N/m^2 are essentially equal to the value of D_{50} in millimeters. These values of τ_{ci}, then, represent the force per unit area required to entrain the gravels.

The next step in the approach is to calculate the force per unit area exerted on the stream bed by different flows. A commonly used formula for computing this bed shear stress is the DuBoys equation (Leopold, *et al.*, 1964),

$$\tau = \gamma_f RS \qquad (3)$$

where τ is the bed shear stress; R is the hydraulic radius, a term originally used in the study of pipe flow and approximated in natural stream channels by depth, d; and S is the energy slope, approximated by the slope of the water surface. The DuBoys equation assumes that flow is uniform (not changing along channel length).

For each gravel study site, we surveyed the channel cross section and longitudinal profile (bed, water surface, and high-water-mark elevations along the length of the channel) and constructed reach maps depicting the occurrence of the gravels in relation to flow features. From the surveys we obtained values of slope and depth with which we could compute shear stresses for the flows observed during field work and for high flows. Field work was conducted on the summer recession limb from August 11-21, 1985 (except for McGee Creek at Logjam, which was surveyed on September 18, 1985). During field surveys, observed high-water marks (trash lines and other evidence of previous high-water levels) were surveyed, and used to develop a water-surface profile for high flows. We inferred that these marks were left by summer snowmelt flows of recent years. Where high-water marks were absent or very poorly defined, we constructed high-water surface profiles by interpolation between riffle crests. This technique only approximates depths but should produce reasonably reliable values of slope.

RESULTS

Flushing Flows Estimated from Flow Records

Flushing flows estimated from flow records, long-term average natural flows, and flushing flows proposed by project applicants are presented for each of the study reaches in Table 1. Application of the Montana method (200 percent of Q_{av}) produced the values in column 6. Applicants for hydroelectric projects in the Owens River basin, explicitly recognizing the need for flushing flows, proposed high-flow releases; these were usually expressed as a multiple of the average flow, but no methods were cited (Table 1, columns 7-9). Except for Big Pine Creek, the proposed flows equal or exceed the recommendation of the Montana method.

Flow duration curves for the project streams presented in the license applications were used in the methods of Hoppe (1975) and Beschta and Jackson (1979; as interpreted by Reiser, *et al.*, 1985) to develop the values in columns 10 and 11. All flushing flows proposed by license applicants, except that proposed for Big Pine Creek, exceed the Q_{17} values. Proposed releases for McGee, Rock, Pine, and Horton Creeks also exceed the Q_{05} values, while proposed releases for Big Pine, Tinemaha, and Red Mountain Creeks are less than Q_{05}.

Bed Mobility Observations

Over the 1986 flow season, all tracer gravels were transported from the sample sites, and none were recovered. We determined that the tracers had moved because none were visible anywhere on the bed, and we encountered none when we dug into the bed at the site of emplacement. Substantial changes at the cross sections over the 1986 flow season were documented by reoccupation of our monumented cross sections (Table 2). Some sites experienced net scour, others net fill. In general, bed material at the sample sites was coarser in 1986. Six of the nine sample sites no longer contained deposits of potential spawning gravels. Instead, a coarse gravel or cobble bed occured at the former sample sites, smaller gravels apparently having been washed out by the high flows of 1986. Results of the painted cobble experiment on Pine Creek, which was designed to provide information on the movement of larger particles, were the same. All particles were moved and none recovered.

In the eastern Sierra Nevada 1986 was a wet year, with runoff averaging about 160 percent of normal in the study streams. Instantaneous peak discharges are not available for the study streams, but if the maximum mean daily flow for Pine Creek in 1986 (9.5 m^3/S) is used with a flood frequency curve developed from the data in Blodgett and Bertoldi (1973), a recurrence interval of about seven years is indicated. Because our tracer gravel observations were conducted over a season of unusually high flows, the complete scouring of potential spawning gravels and the movement of the larger particles, to say nothing of the observed channel changes, may not be an annual occurrence. In years when flow is closer to (or less than) normal, potential spawning gravels may be recruited to the system, and existing deposits may be stable.

Flushing Flows Computed from the Entrainment Function Method

Values of critical shear stress, computed by applying the Shield's function to the D_{50} of our gravel samples, are presented in column 3 of Table 2. Values of depth and slope measured from field surveys on the seasonal recession limb (August 1985) are presented in columns 5 and 6. From these values of depth and slope, we computed the values of shear stress presented in column 7. Flows measured or estimated for the surveyed conditions are presented in column 4. Values of depth and slope at inferred high water conditions are presented in columns 8 and 9, with the corresponding values of shear stress given in column 10.

For seven of the ten samples, the computed shear stress available from the August flows equalled or exceeded that required for entrainment (bold values in column 7). If correct, these results would indicate that the gravels should have been in motion. However, the gravels were not in

TABLE 1. Flushing Flows Proposed by Applicants and Computed from Flow Duration Curves With Unimpaired Average Monthly Flows for Comparison.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	Long-Term Average Flow[a] (m^3/s)				From Montana Method	Proposed Flushing Flow[b]			Flushing Flow Computed from Applicant's Flow Duration Curves (m^3/s)	
Stream	Annual	May	June	July	200 Percent of Annual Average Flow (m^3/s)[c]	Flow (m^3/s)	Percent of Average Flow	Duration (days)	Q_{17}[d]	Q_{05}[e]
McGee Creek	0.844	1.27	2.32	2.01	1.7	1.7-4.2	200-500	5	1.4	3.1
Rock Creek	0.858	1.47	2.32	1.90	1.7	2.6-4.3	300-500	3-5	1.3	2.7
Pine Creek	1.34	2.15	3.77	3.03	2.7	4.0-6.7	300-500	3-16	2.0	4.5
Horton Creek	0.236	0.340	0.595	0.566	0.47	0.85	360	1.5[f]	0.3	0.7
						0.57	240	6[f]		
Big Pine Creek[g]	1.18	1.28	2.85	3.34	2.4	0.28[h]	30[h]	not stated	2.0	4.5
Tinemaha Creek	0.242	0.221	0.651	0.736	0.48	0.48	200	7	0.4	0.7
						0.24	100	21		
Red Mountain Creek[i]	0.119	0.173	0.249	0.229	0.24	0.24	200	7	0.2	0.5
						0.12	100	21		

[a]From Los Angeles Department of Water and Power gaging records through 1985, except for McGee Creek, which is from application.

[b]Flushing flow in m^3/s computed from percentage of average flow stated in application, except for Horton and Big Pine Creeks, for which flow was specified in application and the percentage of annual average is computed here.

[c]Based on Tennant (1976).

[d]Based on Hoppe (1975) and Hoppe and Finnell (1970) as cited by Reiser, *et al.* (1985). Q_{17} is the flow exceeded only 17 percent of the year.

[e]Based on Beschta and Jackson (1979) as interpreted by Reiser, *et al.* (1985). Q_{05} is the flow exceeded only 5 percent of the year.

[f]Computed from statement in application that 0.85 m^3/s (30 cfs) would occur in 5 percent of June flows and 0.57 m^3/s (20 cfs) would occur in 20 percent of June flows.

[g]Long-term average flow values are adjusted to include flow in Giroux ditches (diverted above the LADWP gage), but flow duration curve was drawn from unadjusted gage data, which would tend to make values artificially low.

[h]Actual releases would be considerably greater than the stated 0.28 m^3/s because average flows for June and July would exceed the project capacity (1.84 m^3/s) by 0.7 m^3/s and 1.2 m^3/s even if no deliberate flushing flow were released.

[i]Flow records for summer months in Red Mountain Creek are artificially low because of diversions upstream of the gage.

motion, as we could clearly observe during field work. The implications of this are discussed below.

DISCUSSION OF FLUSHING FLOW ESTIMATES

Methods for estimating flushing flows from flow records presume that "nature knows best," and that the natural flow regime is optimal (or at least adequate) to maintain gravel quality. The flow record methods were developed by observing flushing on natural streams and selecting a statistic that corresponded to the flows at which flushing occurs. This statistic is then used to prescribe flushing flows on other streams. Within a region of relatively homogeneous hydrologic characteristics, it is reasonable to expect that a statistic derived from the study of one stream might be applicable to another, but there is no *a priori* reason to expect the statistic to correctly specify flushing flows in a region having other hydrologic and geomorphic characteristics.

The magnitude and seasonal pattern of flows in a stream depend on many watershed variables (e.g., climate, vegetation, relief, and lithology). Because these independent variables differ from region to region, flow regimes differ in magnitude and seasonal timing. For example, streams of the humid East, which receives year-round rainfall, display less seasonal flow variability than do streams of coastal California, where most runoff is in direct response to winter rains. The latter, in turn, display a seasonal pattern very different from that of streams in the eastern Sierra Nevada, where the vast majority of stream flow is derived from summer snowmelt.

The Montana method (Tennant, 1976) was developed from observations on streams of the northern Great Plains and Rocky Mountain states; the Hoppe method, on the Fryingpan River in Colorado (Reiser, *et al.*, 1985) and the Q_{05} method on coastal Oregon streams (Reiser, *et al.*, 1985). One way to evaluate the applicability of these methods, derived elsewhere, to streams of the eastern Sierra Nevada would be to compare their prescribed flushing flows with naturally occurring high flows during the snowmelt season, on the assumption that the naturally occurring high flows are optimal. Long-term average flows for May, June, and July are presented for each study stream in columns 3-5 of Table 1. (The values for Red Mountain Creek must be discounted because they are artificially lowered by upstream diversions during summer months.) In most years, actual flows at the peak

TABLE 2. Calculated Shear Stresses Required for Entrainment and Calculated Shear Stresses Available on Recession Limb and at High Flow.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
		Shear Stress Needed for Entrainment	Shear Stress, τ_r, Available on Recession Limb from DuBoys Equation				Shear Stress, τ_{hf}, Available at High Flow from DuBoys Equation			
Sample No.	Sample Site	$\tau_{ci}(N/m^2)$	$Q(m^3/s)$	$d_{(m)}$	$s(^m/m)$	$\tau r(N/m^2)$	$d_{(m)}$	$s(^m/m)$	$\tau_{hf}(N/m^2)$	Ratio τ_{hf}/τ_{ci}
	McGEE CREEK									
1	At Red Root	10	0.76	0.41	0.01	**40**	0.96*	0.07	659	66
2	At Log Jam	30	0.54	0.34	0.004	13	0.52**	0.041	209	7
	PINE CREEK									
3	01+09	16	0.65	0.18	0.006	11	0.55**	0.034	183	11
4a	01+45 (top 6 cm only)	29	0.65	0.24	0.015	**35**	0.55**	0.034	183	6
	HORTON CREEK									
5	01+05	13	0.23	0.20	0.030	**59**	0.18*	0.095	168	13
6	00+38	40	0.23	0.27	0.015	40	0.85*	0.113	942	24
7	00+19	14	0.23	0.14	0.025	**34**	0.73*	0.113	809	58
	BIG PINE CREEK									
8	At trailer park	10	1.44	0.37	0.027	**98**	0.76**	0.045	335	34
	TINEMAHA CREEK									
9	Washed-out beaver dam	21	0.40	0.14	0.036	**49**	0.85*	0.067	559	27
10	Big beaver dam (01+07)	8	0.31	0.08	0.004	3	0.61**	0.08	479	60

*High-water-surface elevations interpolated from surveyed high-water marks.
**High-water surface assumed by interpolation between low-water riffle crest elevations. Resultant depth may be inaccurate.
NOTE: Bold values (column 7) indicate that computed shear stress on recession limb exceeds stress needed for entrainment. However bed material was not in motion, indicating that shear stress computed for flow was unrealistically high as a result of nonuniform flow conditions.

of the snowmelt hydrograph are much greater than the monthly averages presented here, but these values can be used as reasonable minimum values for naturally occurring annual high flows in the study streams.

Flushing flows prescribed by the Montana method (200 percent of Q_{av}; Table 1, column 6) are lower than the maximum mean monthly flow by an average of 26 percent. (Red Mountain Creek has been excluded from this analysis.) Thus, the Montana method prescribes flushing flows that are considerably lower than the naturally occurring high flows. In most cases, license applicants expressed their proposed flushing flows as multiples of mean annual flow (Table 1, colunns 7 and 8). Many of these proposed releases exceed 300 percent of the mean annual flow and are comparable to or greater than the natural peak monthly means (columns 4 and 5). Thus, they can be considered better approximations of the natural flow regime. The flushing flow estimates developed from the Q_{17} of the flow duration curves (column 10) are consistently lower than the natural monthly maxima (columns 4 and 5), and Q_{05} (column 11) consistently greater.

The assumption underlying the foregoing comparison, and, indeed, the entire use of flow records to develop flushing flows, is that the natural regime is ideally adjusted to maintain gravel quality, and therefore the flushing flow release should mimic the natural regime in some way. However, there are cases in nature where the supply of fine sediment is so great (because of drainage basin lithology or upland erosion) that the natural stream flow is inadequate to flush it out. (Kanab Creek in northern Arizona is an extreme example.) Likewise, stream power may be so high that not only fine material but also gravels themselves may be flushed out at most sites. (The Tuolumne River in the western Sierra Nevada and our study streams are examples.)

Accordingly, it would seem preferable to specify through observation or calculation the actual flows at which gravel begins to move in the study streams. Because our field work did not coincide with the annual period of high flows, we could not specify the threshold of movement from direct observation. Our attempt to apply the DuBoys equation to compute bed shear stresses exerted by different flows was hampered by the fact that the equation assumes uniform flow, a condition not met in the study reaches.

Uniform flow is an ideal never actually achieved in natural streams, although it can be approximated in large, regular channels. The stream reaches studied have irregular channels dominated by boulder cascades. These conditions give rise to flow patterns that are distinctly nonuniform. (Characteristics of steep, boulder-bed streams are reviewed by Kondolf, *et al.*, in press.) As noted above, potential spawning gravels generally occurred only in reaches of gentler-than-average slope where flow conditions might be more uniform than elsewhere in the project reaches (Kondolf, *et al.,* in press), but mapping of current directions and results of our calculations indicate that deviations from uniform flow were substantial.

As noted above, shear stresses (computed from the DuBoys equation) for August recession limb conditions equalled or exceeded the critical shear-stresses computed from the Shield's function for seven of the ten samples. However, the gravels were not in motion, as we could plainly observe through the clear water. From this result, we conclude that the nonuniform flow conditions in the small, steep, irregular channels of the study reaches render the DuBoys equation inapplicable at most of our sample sites. Shear stresses are so high over most of the streambed that gravel deposits tend to be in sites of flow divergence, often behind boulders (Kondolf, *et al.,* in press). This suggests that, in many cases, gravels are deposited in microenvironments of lower shear stresses; if exposed to the main flow at the cross section, they would be swept away (as predicted by the computed shear stress values). Bathhurst (1986) noted that transverse components of water surface slope can be important in boulder-bed channels. Thus, to adequately characterize the hydraulic microenvironment of the gravel spawning sites would require detailed mapping of bed and water-surface topography at a range of flows.

For example, one of the sites whose computed shear stress exceeded that required for entrainment was McGee Creek at Red Root. The reach map (Figure 2) shows that the gravel sample was located near the left bank, downstream of a plunge pool from which current was directed towards the right bank. Had we made sufficiently detailed measurements, we would probably have detected a component of the water-surface slope towards the right bank and found that the average channel slope did not accurately reflect the slope specific to the microenvironment of the gravel deposit.

Shear stresses computed from survey data believed to reflect annual high flows exceeded critical shear stresses from 6 to 66 times (Table 2, column 11). The degree to which these high-flow shear stress values exceed critical implies that the gravels are mobilized at these high flows, even allowing for the imprecision of the approach. If the high flow conditions are, indeed, the annual snowmelt flows, then annual turnover of the gravel is implied. This is consistent with the complete washout of tracer gravels observed over the 1986

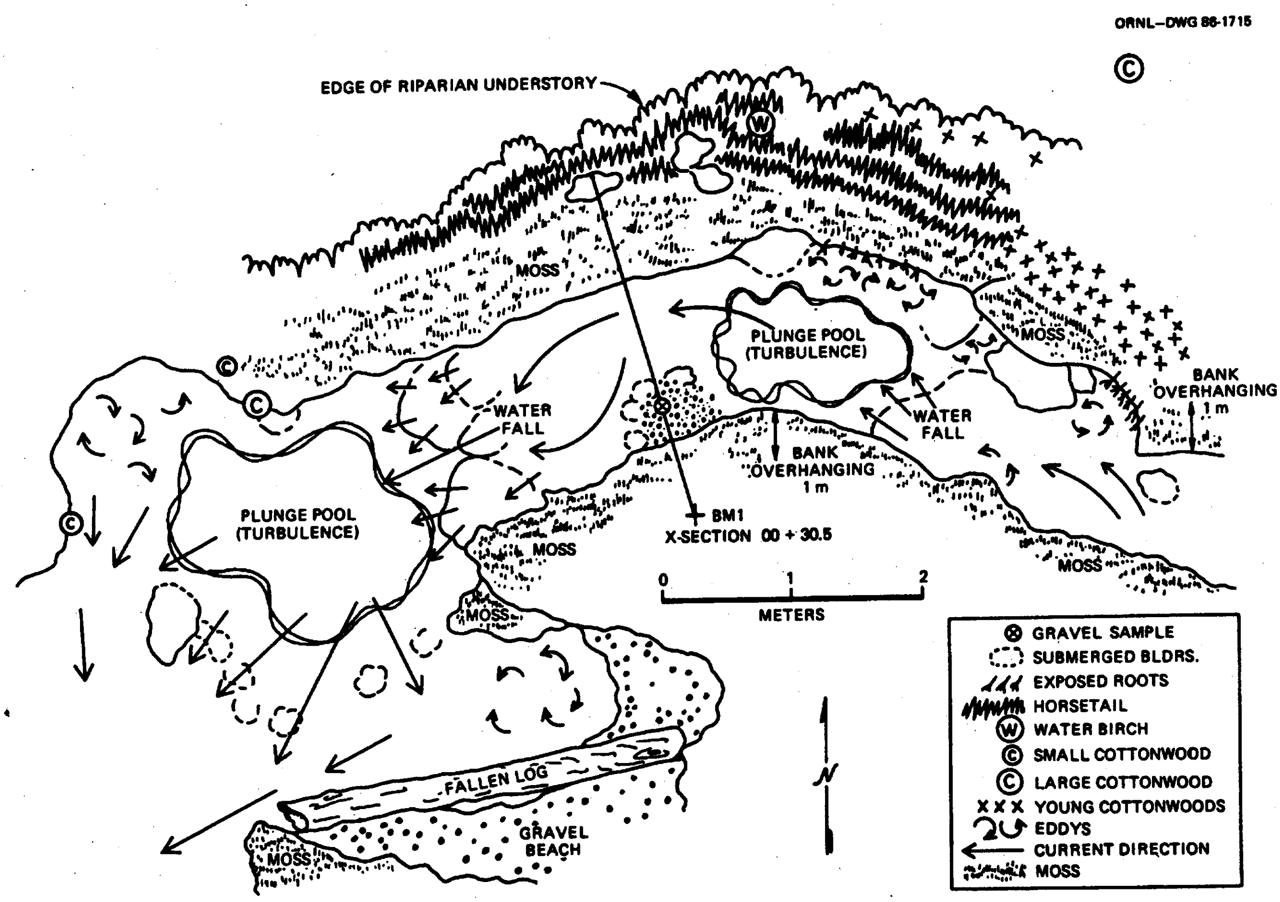

Figure 2. Reach Map for McGee Creek at Red Root Site. Location of gravel sample and channel cross section shown in relation to flow features and bank configuration. (Map by A. V. Kondolf from field observations August 11, 1985.)

flow season. However, because 1986 was an unusually wet year (with 160 percent of normal runoff), the generality of the results could be questioned. However, tracer gravel observations by T. Felando (Inyo National Forest, Bishop, pers. comm., 1985) indicated that gravels at a nearby site on Pine Creek were mobile down to a depth of about 15 cm in 1985, a year with 95 percent of normal runoff and a recurrence interval on Pine Creek of about 1.3 years. Thus, some flushing of gravels on an annual basis is suggested.

It was our intention to specify the flow at which gravel was entrained by computing shear stress values for flows intermediate to the observed August recession limb and the inferred snowmelt peak flows. However, this was not possible because of the unrealistic results obtained from application of the DuBoys equation to the site.

Effects of Sluicing Accumulated Sediments from Diversion Structures

The analyses presented above were aimed at specifying the magnitude of flow releases required to "turn over" gravels in the diverted reaches. However, the projects will affect not only the magnitude and timing of flows in the diverted reaches but also the timing of sediment delivery, because diversion structures will trap bedload sediment (sand and gravel) from upstream (Milhous, 1985). Unlike larger dams, diversion structures (typically less than 3 m high) do not permanently trap large volumes of sediment, because they have little dead storage and are typically equipped with gates through which accumulated sediments can be flushed during periodic flushing flow releases. Thus, sediment from above the diversions will be introduced to the downstream reaches in pulses rather than being spread out over the months of natural snowmelt flow.

Sediment transport rates in streams reflect a balance between sediment supplied from the watershed and the transporting force available from the stream flow. The paucity of sediment stored in-channel suggests that our study reaches are sediment starved (capable of moving far more sediment than is supplied from upstream reaches). This mostly reflects the fact that flows in these steep streams have tremendous transporting power and does not necessarily imply that sediment yields from the basins are small. No sediment transport data exist for the study streams, but we have noted that beaver dams, logjams, and an existing diversion have accumulated substantial quantities of sediment behind them, implying that the diversion structures would likewise accumulate sizable quantities of sediment.

It is difficult to predict how pulses of sediment released from the dams will move downstream, but field observations in the project reaches and tracer gravel studies elsewhere (Kondolf and Matthews, 1986) suggest that the material will be quickly sorted into a fine fraction that may remain in suspension, traversing the entire reach, and coarser fractions that will leapfrog from depositional site to depositional site. The total distance traveled for each fraction will depend on flow magnitude and duration, but since both will be reduced in diverted reaches, we can expect more of the flushed sediment to remain in the diverted reach than under natural conditions. If the reaches retain more gravel, this could improve the spawning gravel resource; if they retain more sand as well, this could degrade the resource.

SUMMARY AND CONCLUSIONS

Methods for estimating flushing flows from flow records, developed from studies conducted in other localities, produced widely differing results when applied to the study streams. Two criteria, 200 percent Q_{av} and the Q_{17} from the flow-duration curve, are consistently lower than the mean monthly flows during the snowmelt peak. Another criterion based on the flow-duration curve, the Q_{05}, is consistently higher than the mean monthly flows at snowmelt. With one exception (Big Pine Creek), flushing flow releases proposed by license applicants ranged from 200-500 percent Q_{av}; those exceeding 300 percent Q_{av} equalled or exceeded the mean monthly flows at snowmelt.

There is no *a priori* reason to expect a statistic that corresponds to the flushing flow on one stream to apply to streams in a different hydrologic and geomorphic setting. Thus, the lack of agreement between methods should come as no great surprise. Moreover, all these methods implicitly assume that the natural flow regime is optimal and should be emulated. However, on some streams the natural flow regime may be less than or far in excess of that required to flush the gravel. This consideration suggests a more mechanistic approach: specifying the flushing flow as being the flow at which gravel begins to move, based on observations of tracer gravel movement or tractive-force calculations. Our field period did not encompass the annual high flows, so we could not directly observe bed material movement. To document bed mobility over the subsequent flow year (1986), we painted our gravel samples and replaced them in the bed at their original sites in four of our study reaches. All these tracer gravels were completely swept away from our sample sites by the flows of 1986. In six of the nine sites, only a coarse gravel or cobble bed was found at the former site of potential spawning gravel. However, 1986 was a wet year, with about 160 percent of normal runoff in our study streams, so these results do not necessarily imply complete mobility of gravels in lower flow years.

In an attempt to calculate the flows at which the gravels should be entrained, we sampled gravels and collected hydraulic data at the sites and used the DuBoys equation and Shield's function to compute bed shear stress (force per unit area exerted on the bed by the flow) and critical shear stress (shear stress at the threshold of motion). The DuBoys equation assumes uniform flow, a condition not satisfied in the study reaches. As a result, the bed shear stress values we computed were unrealistically high. This implies that tractive-force approaches, which work well in lower gradient, alluvial channels (where uniform flow is more closely approximated), may not be applicable in steep, boulder-dominated channels like those in this study. Thus, use of flow records and/or bed mobility experiments may be the only viable approaches in some settings.

Because the tractive-force approach did not work well in the study reaches (with their extremely nonuniform flows), we could not directly compare flushing-flow recommendations from flow records with those from tractive-force computations. In this study we did not attempt to determine the optimal duration for flushing flows, although this would be an important variable in flushing flow recommendation.

The proposed new hydroelectric projects may also affect spawning gravels in the diverted reach by changing the timing of sediment delivery. Sand and gravel would be trapped behind diversion structures and released at once during flushing-flow releases. The released sediment would probably sort quickly by size, and each size fraction would leapfrog downstream from depositional site to depositional site. To develop reliable quantitative predictions, however, would require further observations, especially during high snowmelt flows.

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